Self-Similar Secondary Infall: A Physical Model of Halo Formation

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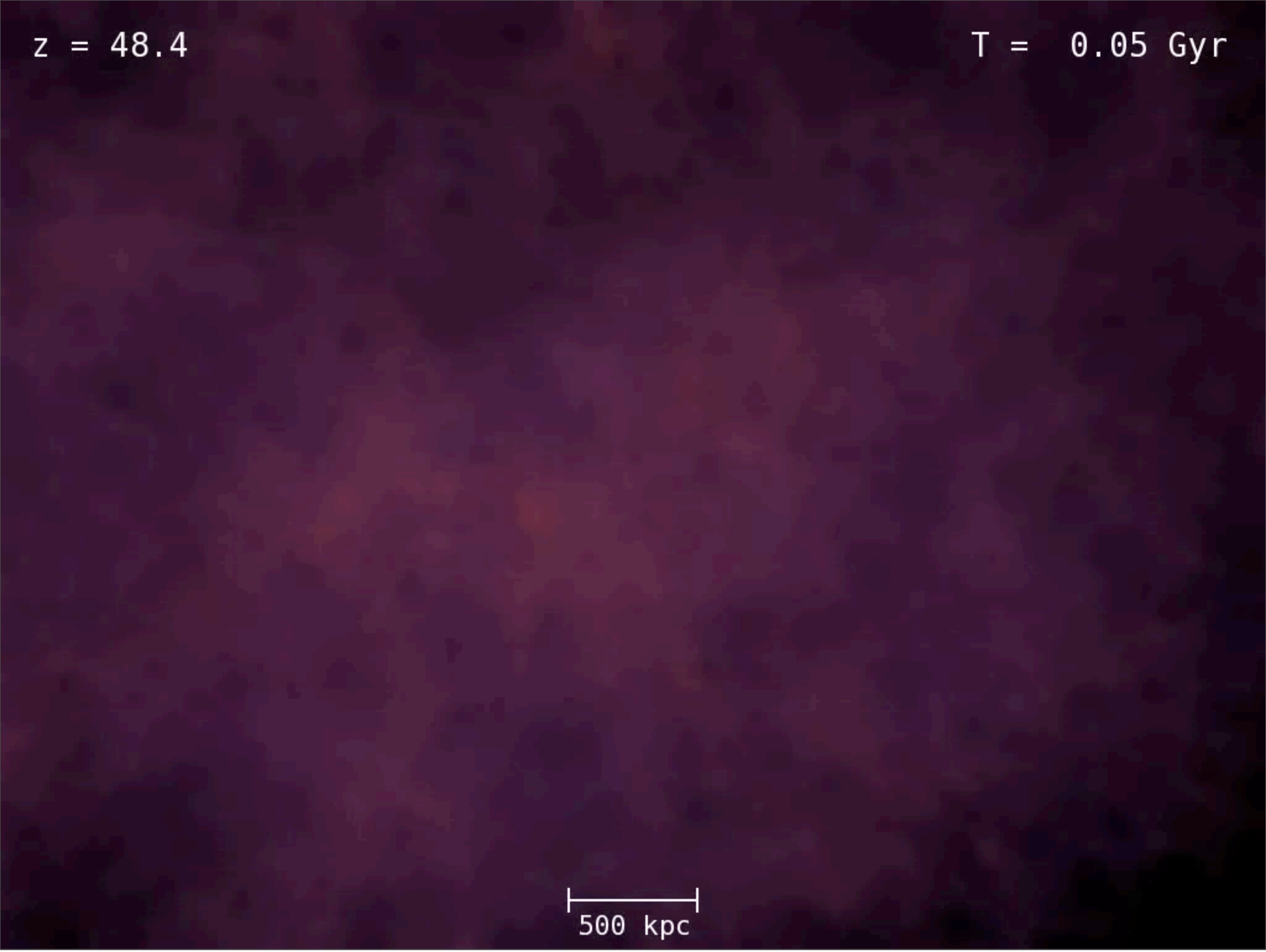
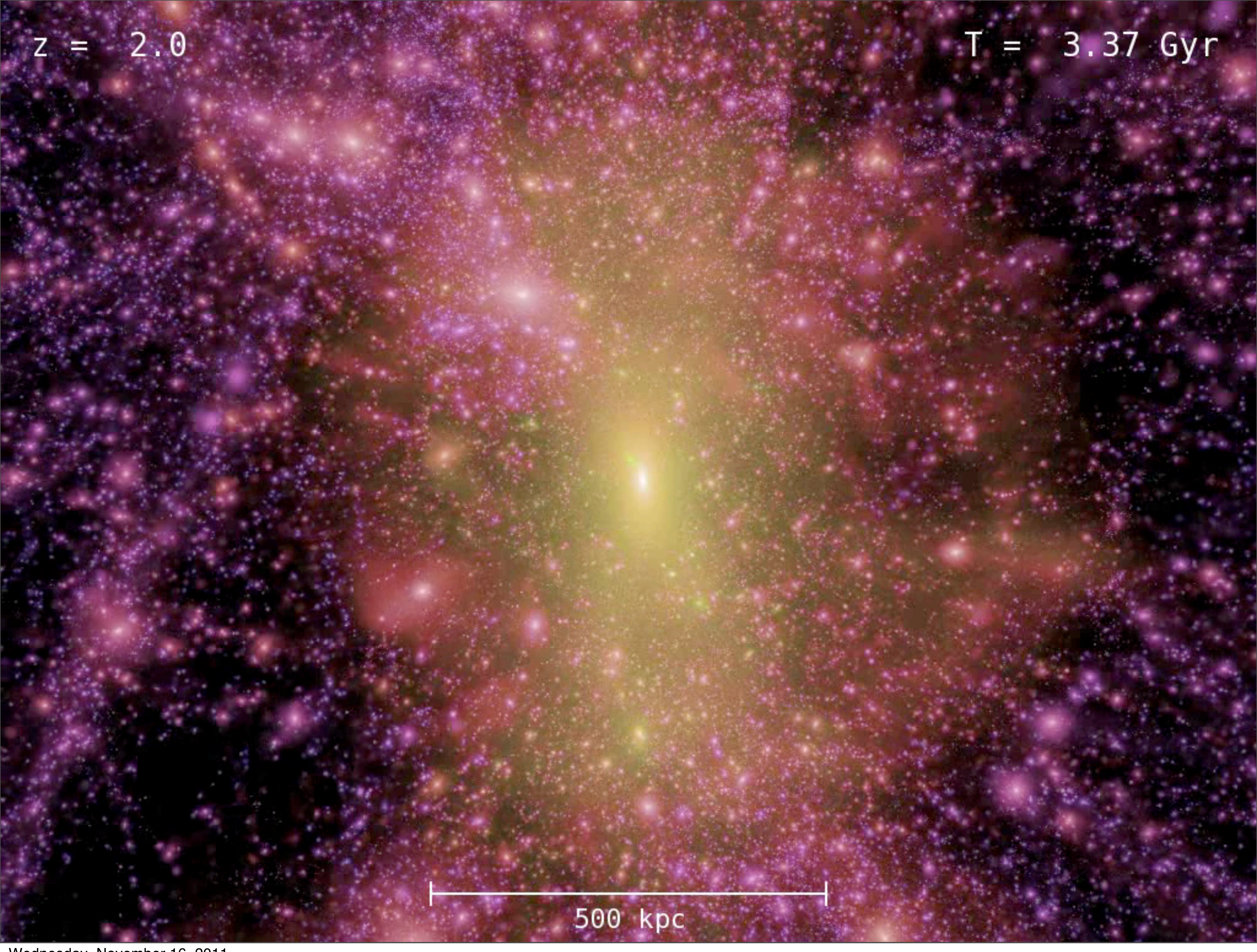
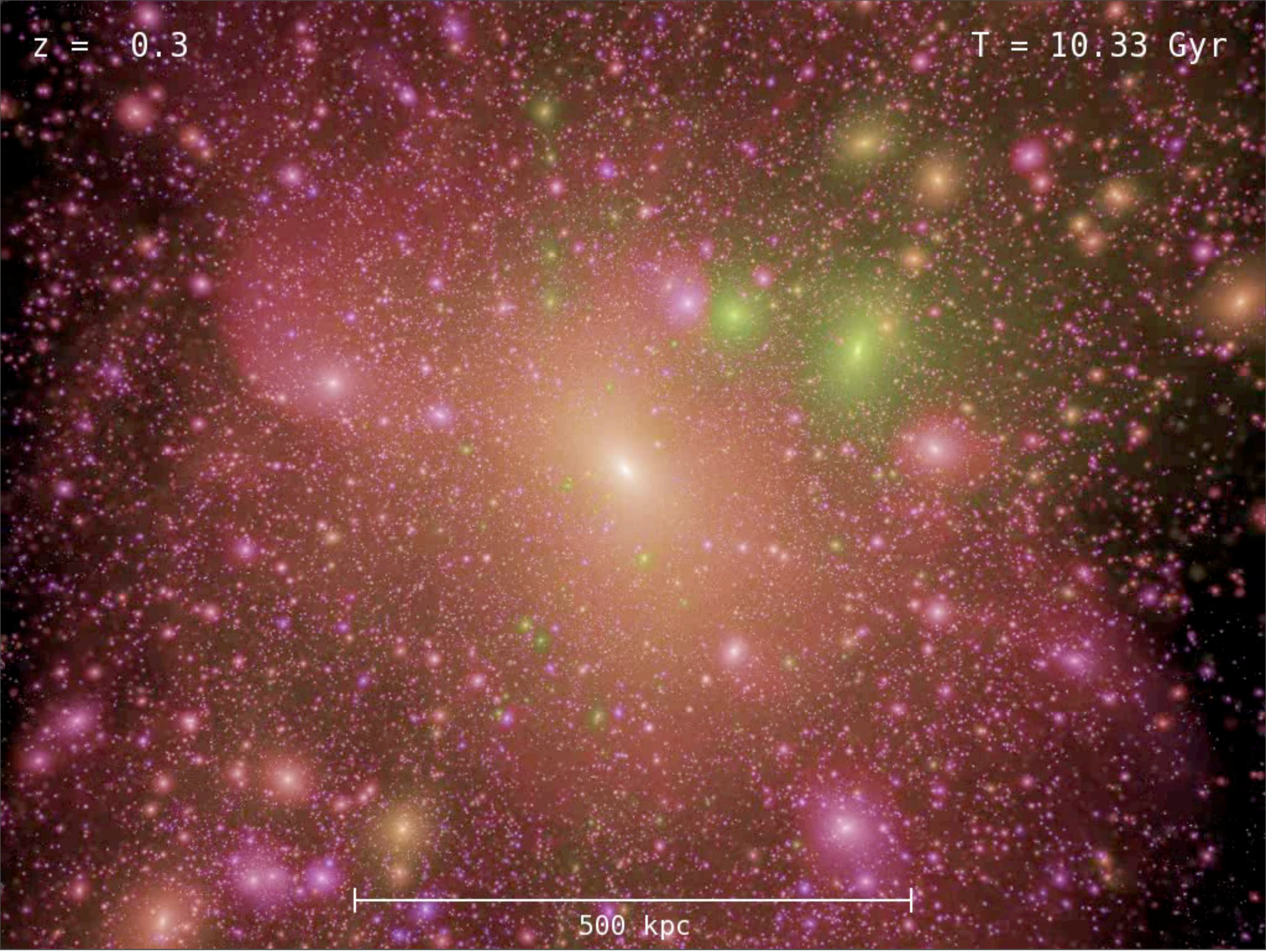
11/15/11


z = 48.4
T = 0.05 Gyr
500 kpc

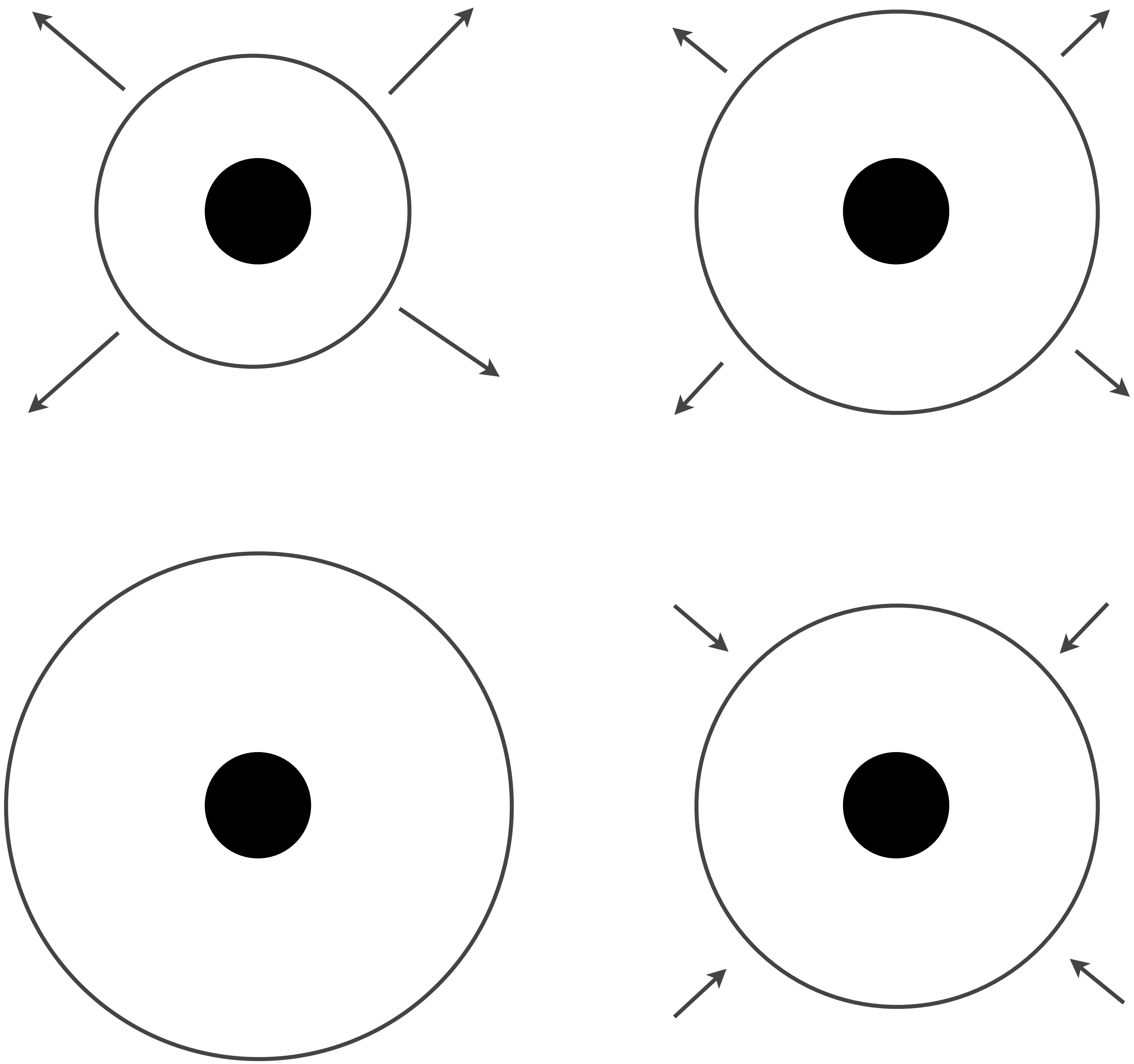

z = 2.0
T = 3.37 Gyr
500 kpc


z = 0.3
T = 10.33 Gyr
500 kpc

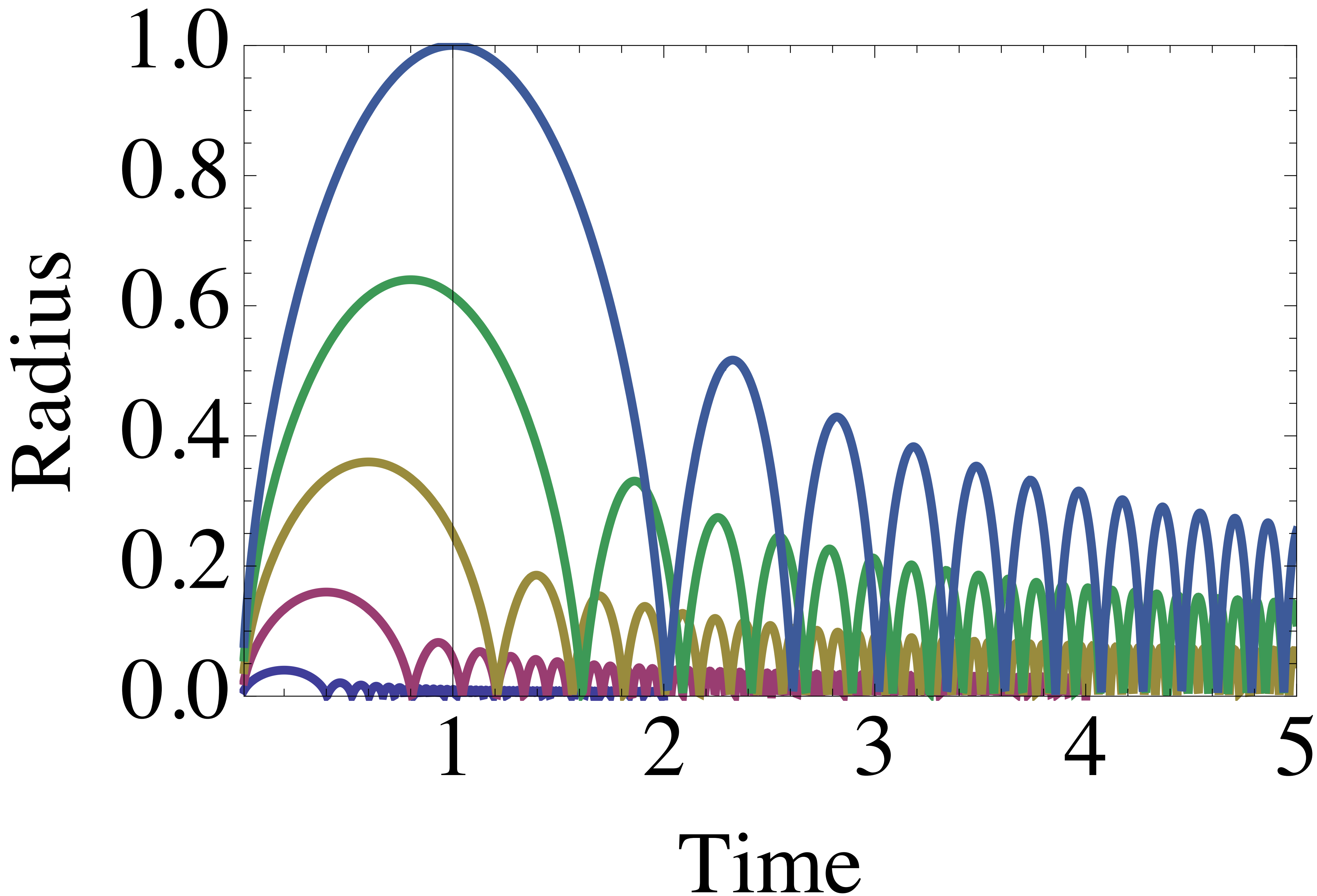
What do (Aquarius) simulations tell us?

- Halos have NFW (Einasto) density profiles.
- The density profile is (roughly) universal.
- The pseudo-phase-space density ρ/σ^3 is universal.

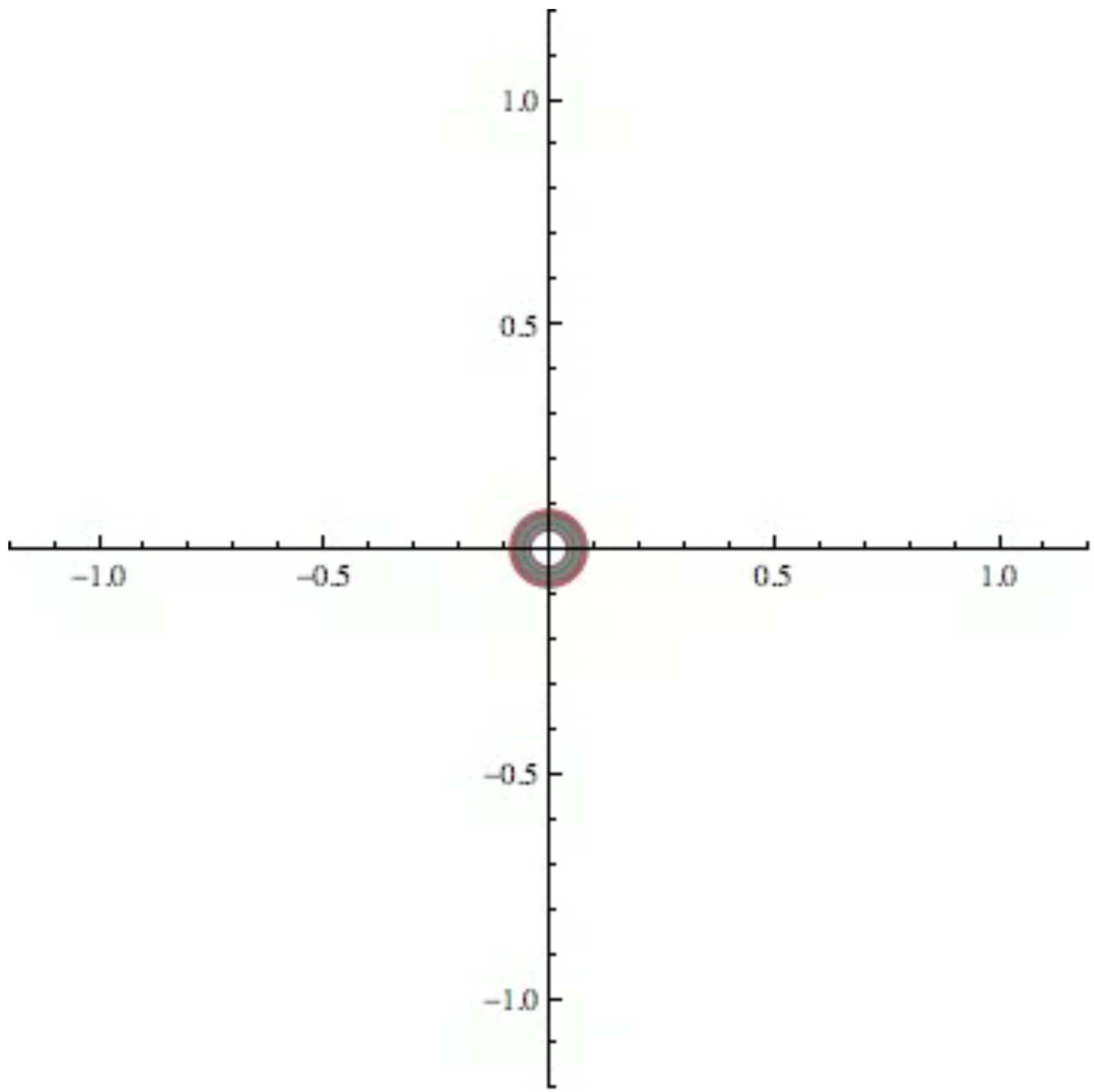
Secondary Infall



Self-Similarity



Self-Similar Secondary Infall



Why?

- Numerically (much) easier.
- Analytically tractable: $\frac{d\ln M}{d\ln r}$ $\frac{d\ln \sigma_r^2}{d\ln r}$ $\frac{d\ln \sigma_t^2}{d\ln r}$

(Some) Criticisms

- Spherical Halo?
- Box Orbits?
- Self-Similar?

Model

- Initial density perturbation: $\delta \propto r^{-n}$

- Particles torqued throughout evolution.

$$L(r,t) = B\frac{r_{ta}^2}{t}\begin{cases}(r/r_{ta})^{-\gamma} & \text{if } t < t_*, \\ (t/t_*)^{\varpi+1-2\beta} & \text{if } t > t_*. \end{cases}$$

- Parameters n, B, γ set by halo mass

- ϖ difficult to constrain analytically.

What do we do Numerically?

- Mass profile depends on the location of all shells.
- Trajectory of shells depends on internal mass profile.
    - 1) Start with an assumed mass profile.
    - 2) Solve for the trajectory of one shell using Newton’s equation.
    - 3) Calculate new mass profile.
    - 4) Iterate.

What do we do Analytically?

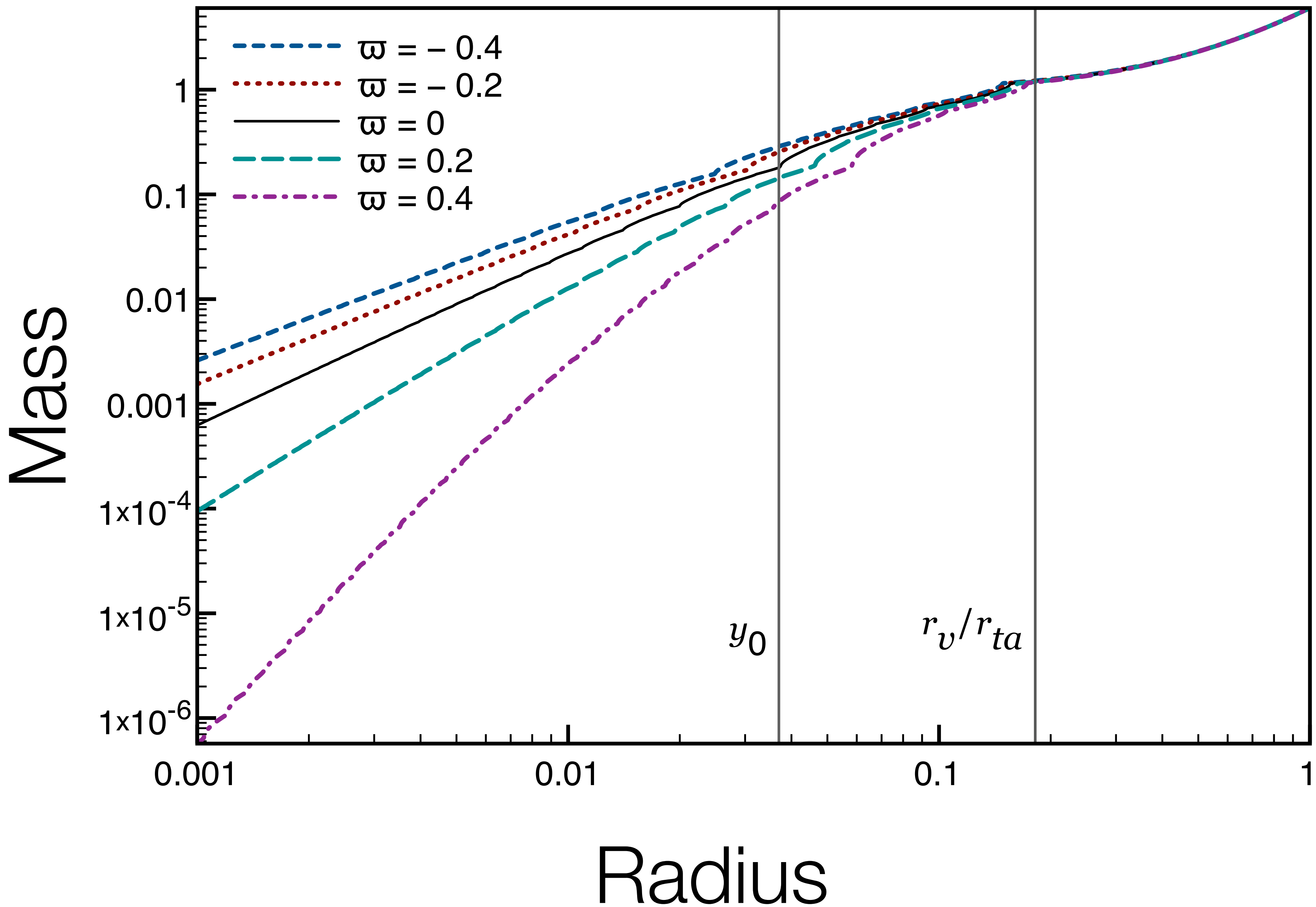
- Parametrize mass profile and variation of apocenter distance:

$$M(r,t) = \kappa(t) r^{\alpha}$$

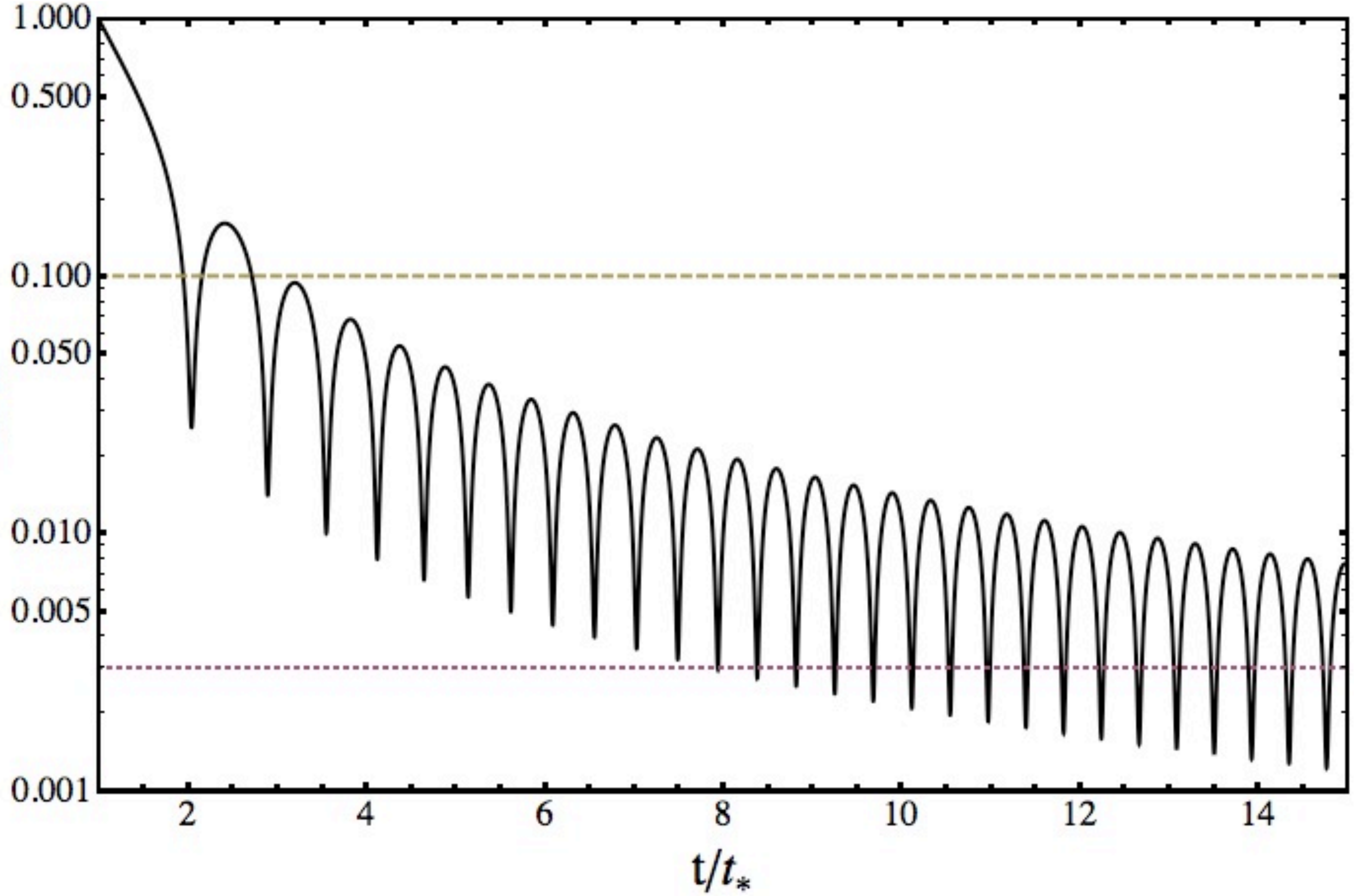
$$r_a/r_* = (t/t_*)^q$$

- Use adiabatic invariance and a mass consistency relationship to constrain both exponents.

Model Results:
Mass Profile



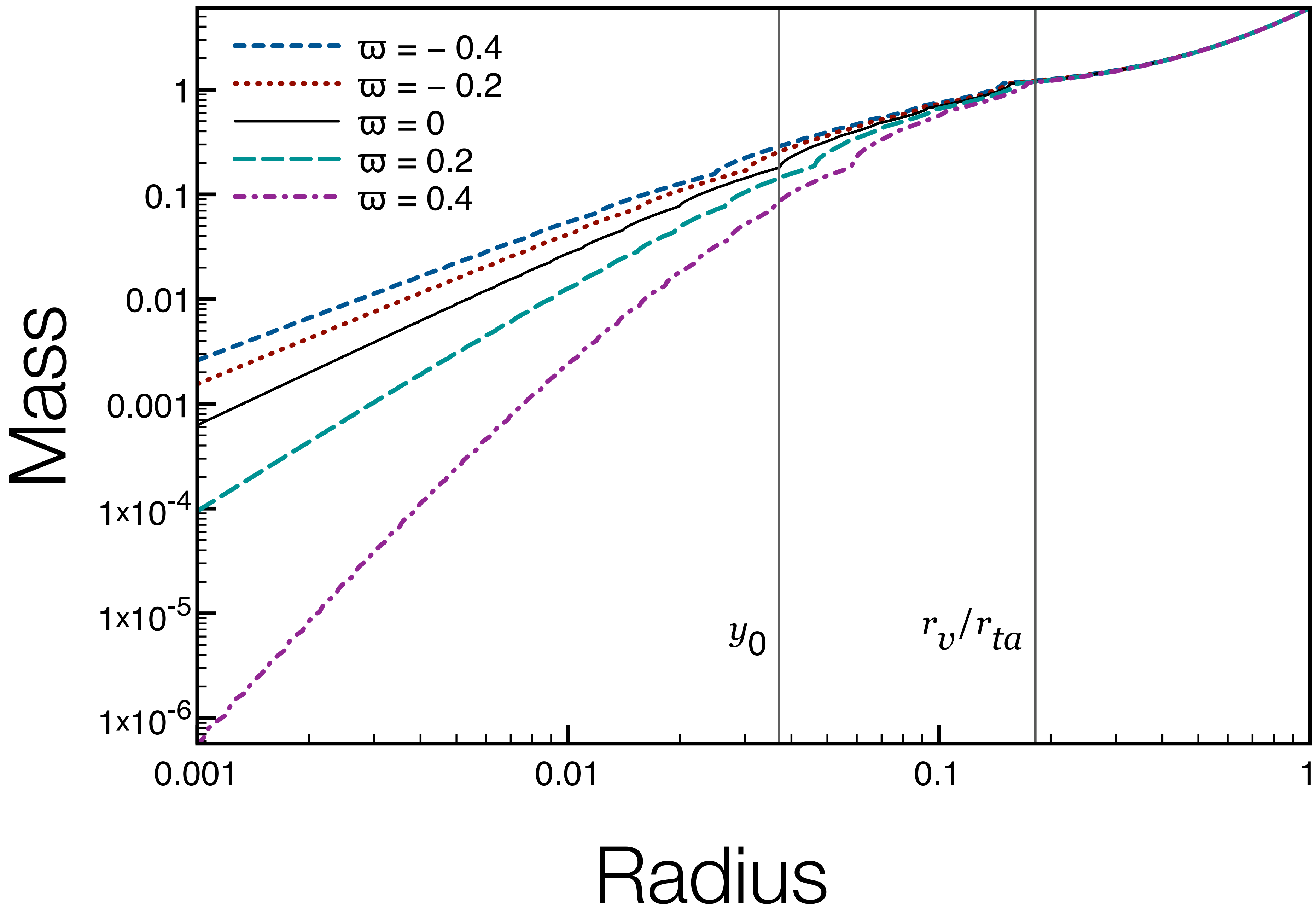
Location of Shells



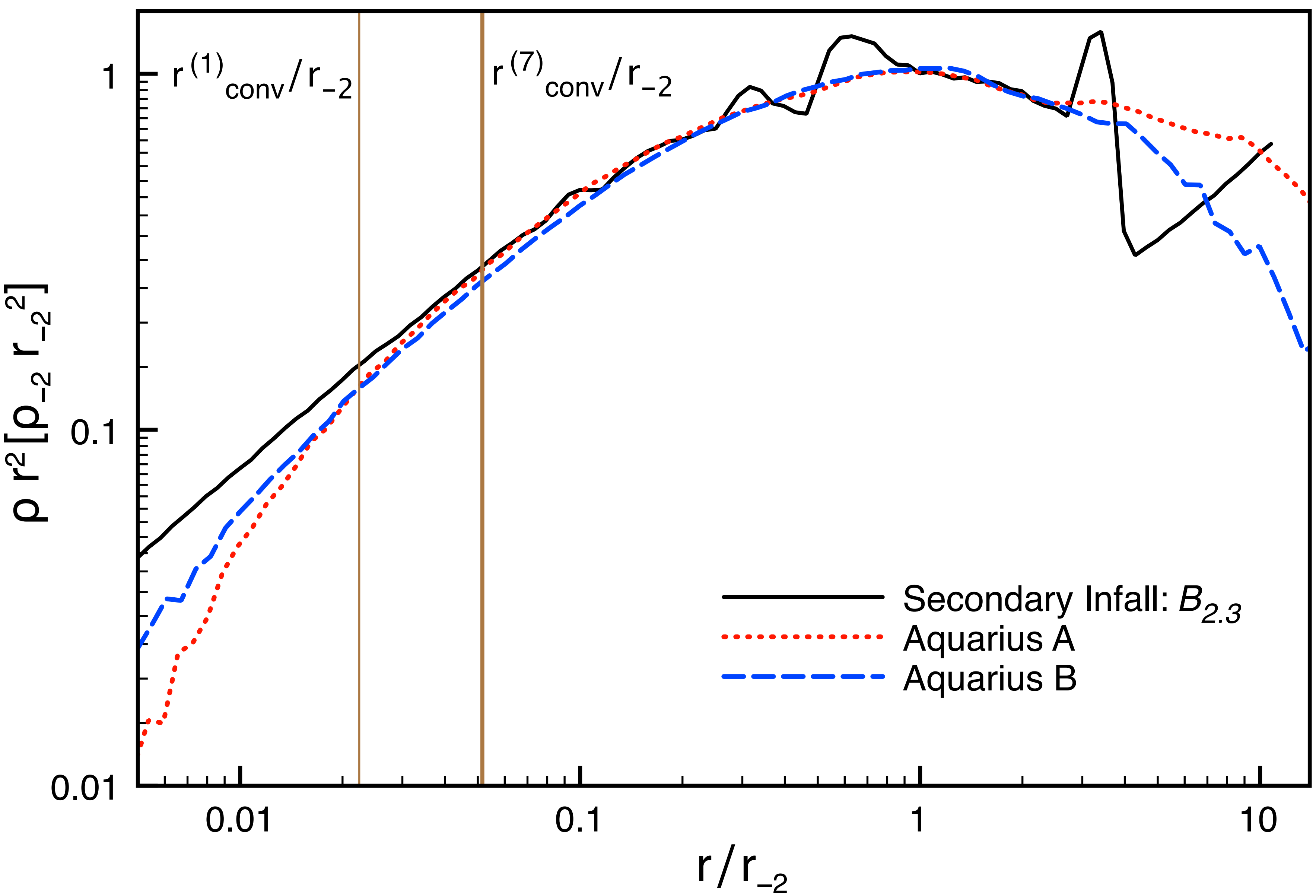
Radius

Turnaround Time

Model Results: Mass Profile

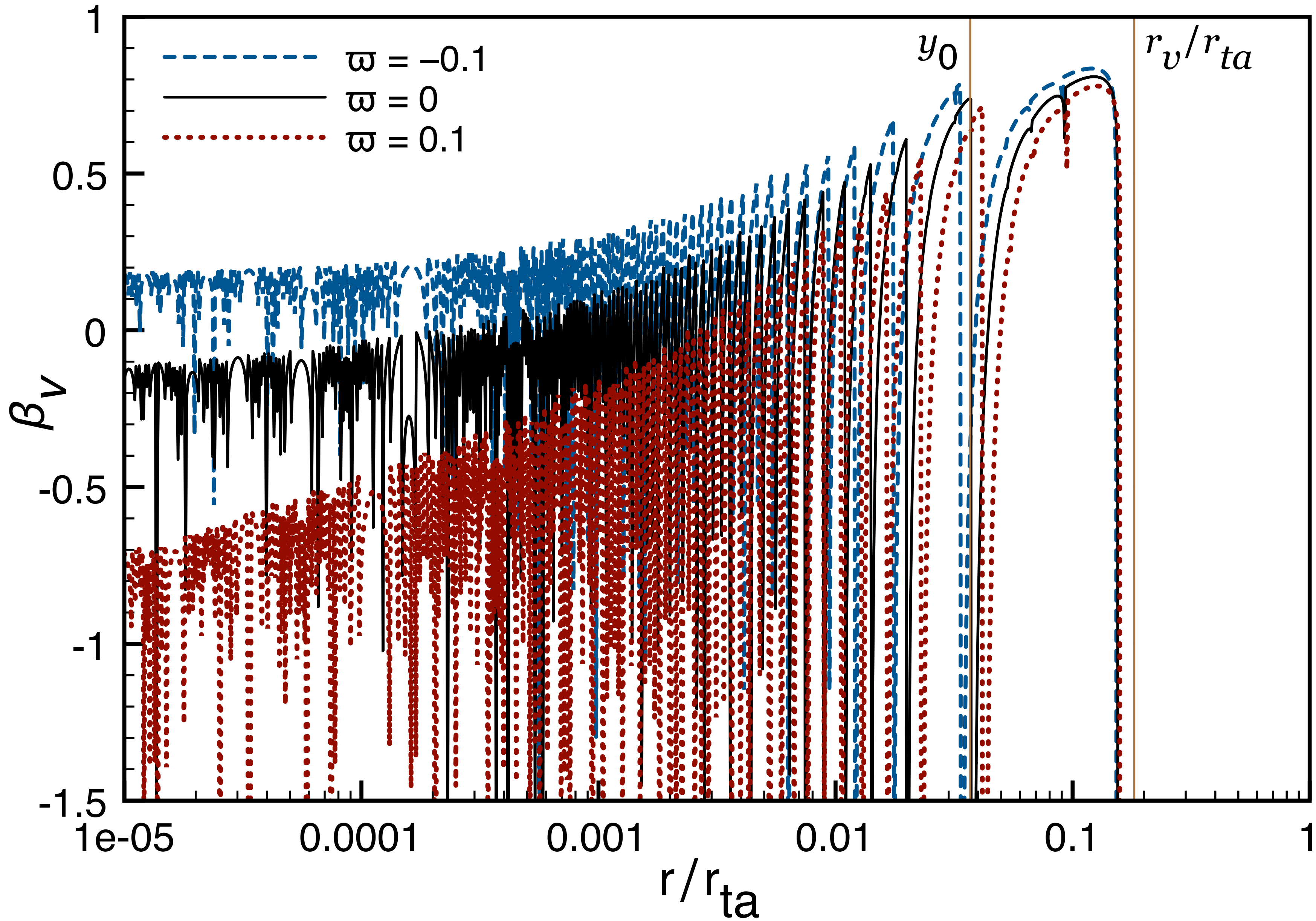


Model vs N-body

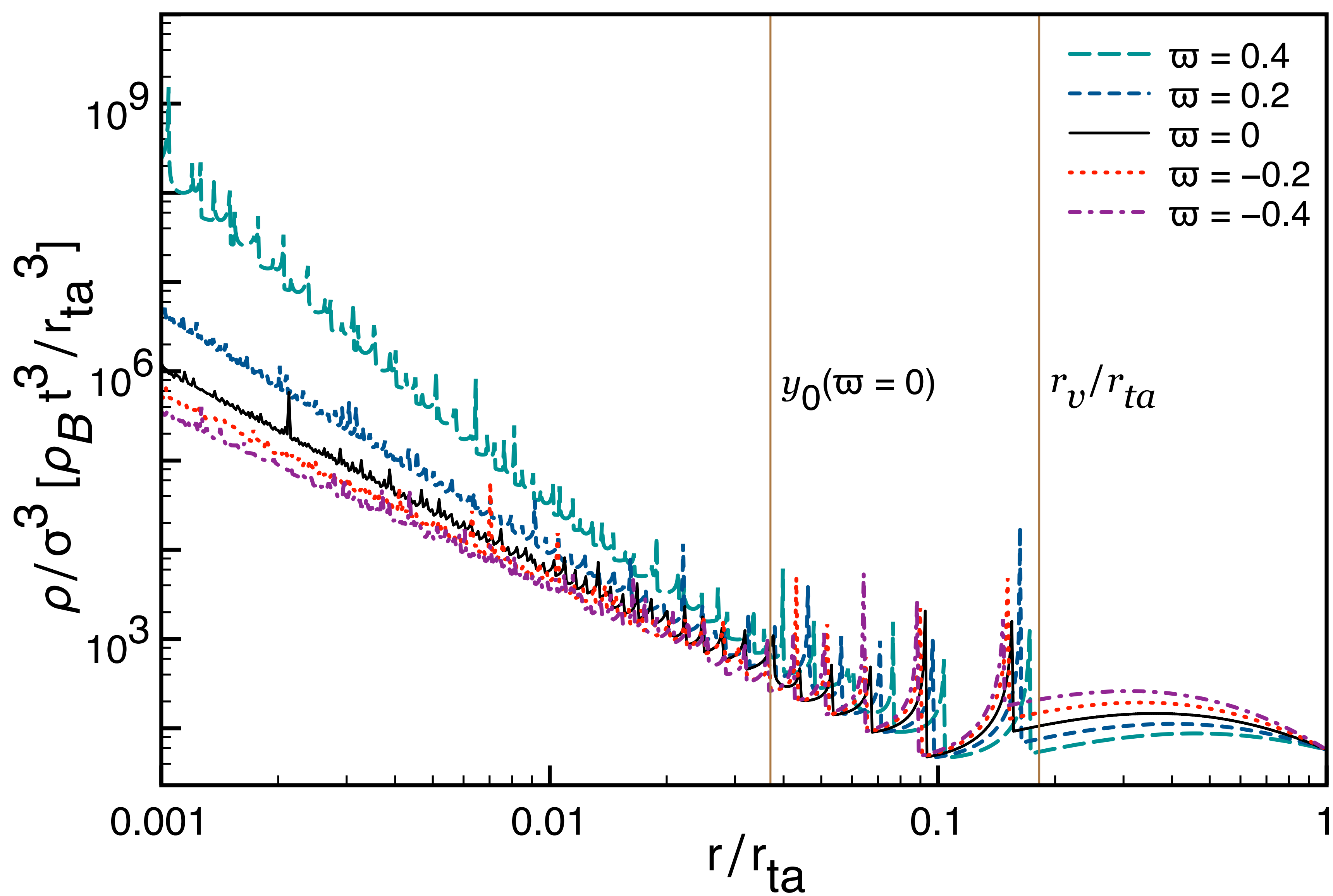


Model Results: Velocity Anisotropy

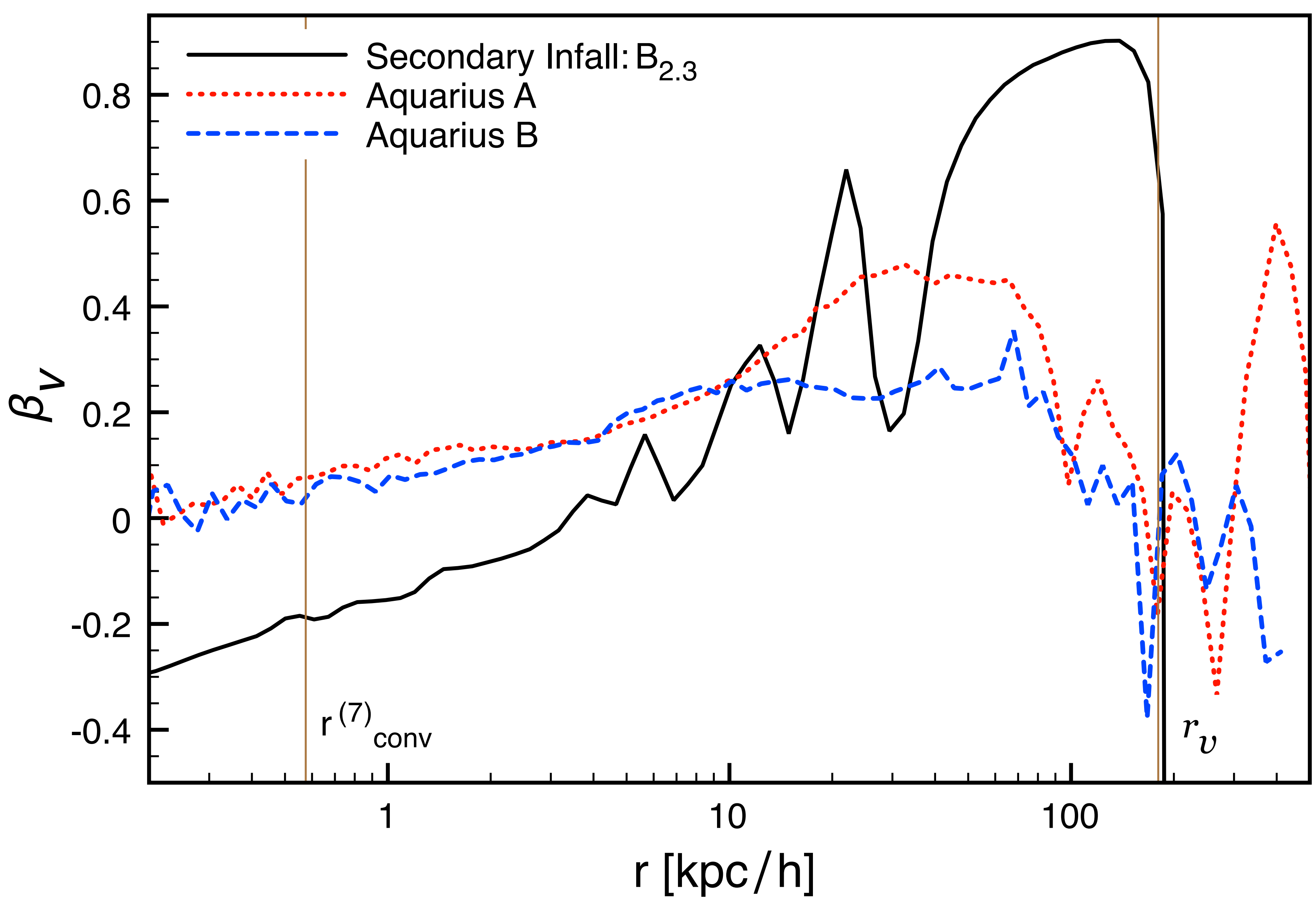
$$\beta_v \equiv 1 - \sigma_t^2/2\sigma_r^2$$



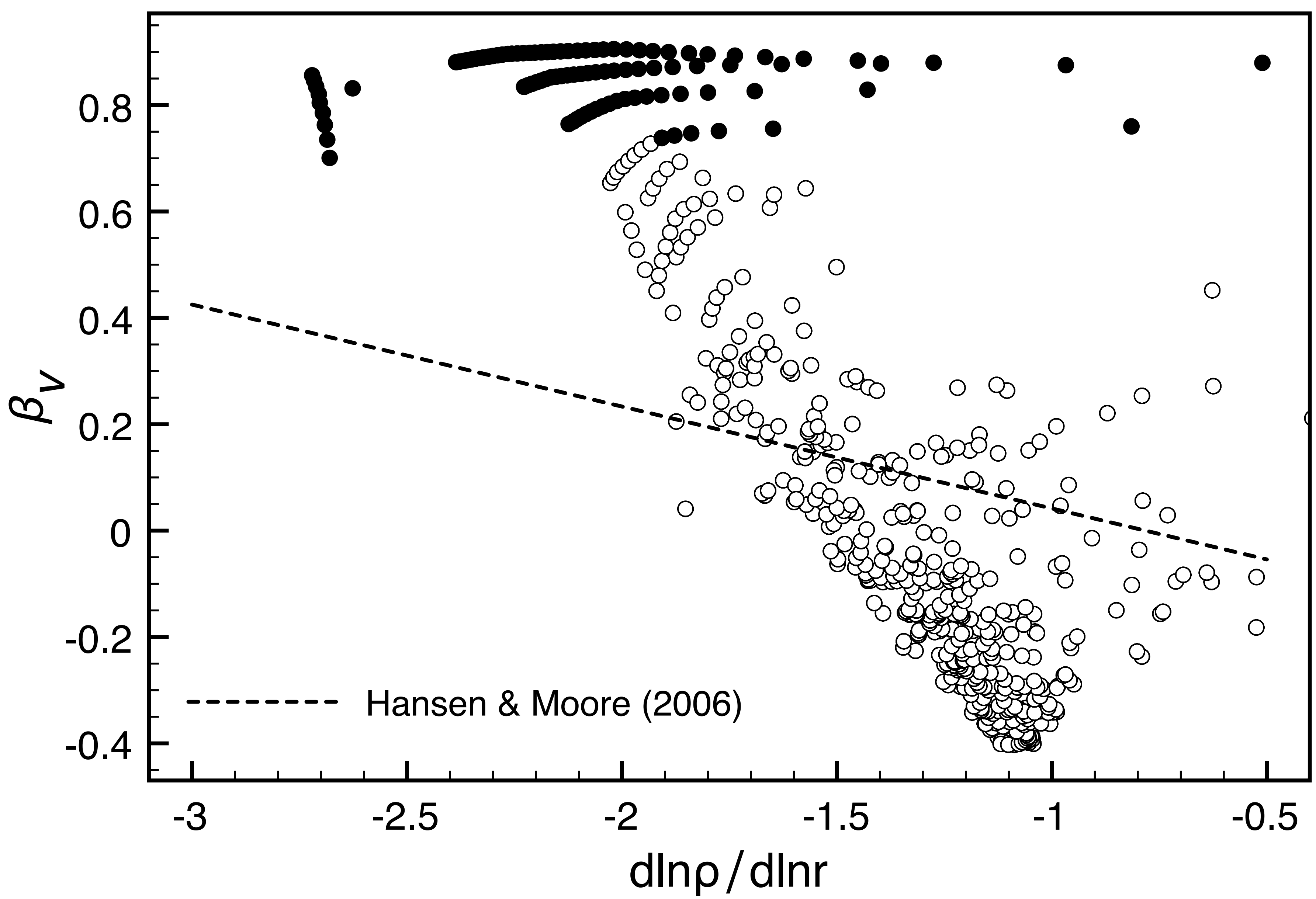
Model Results: Pseudo-Phase-Space Density



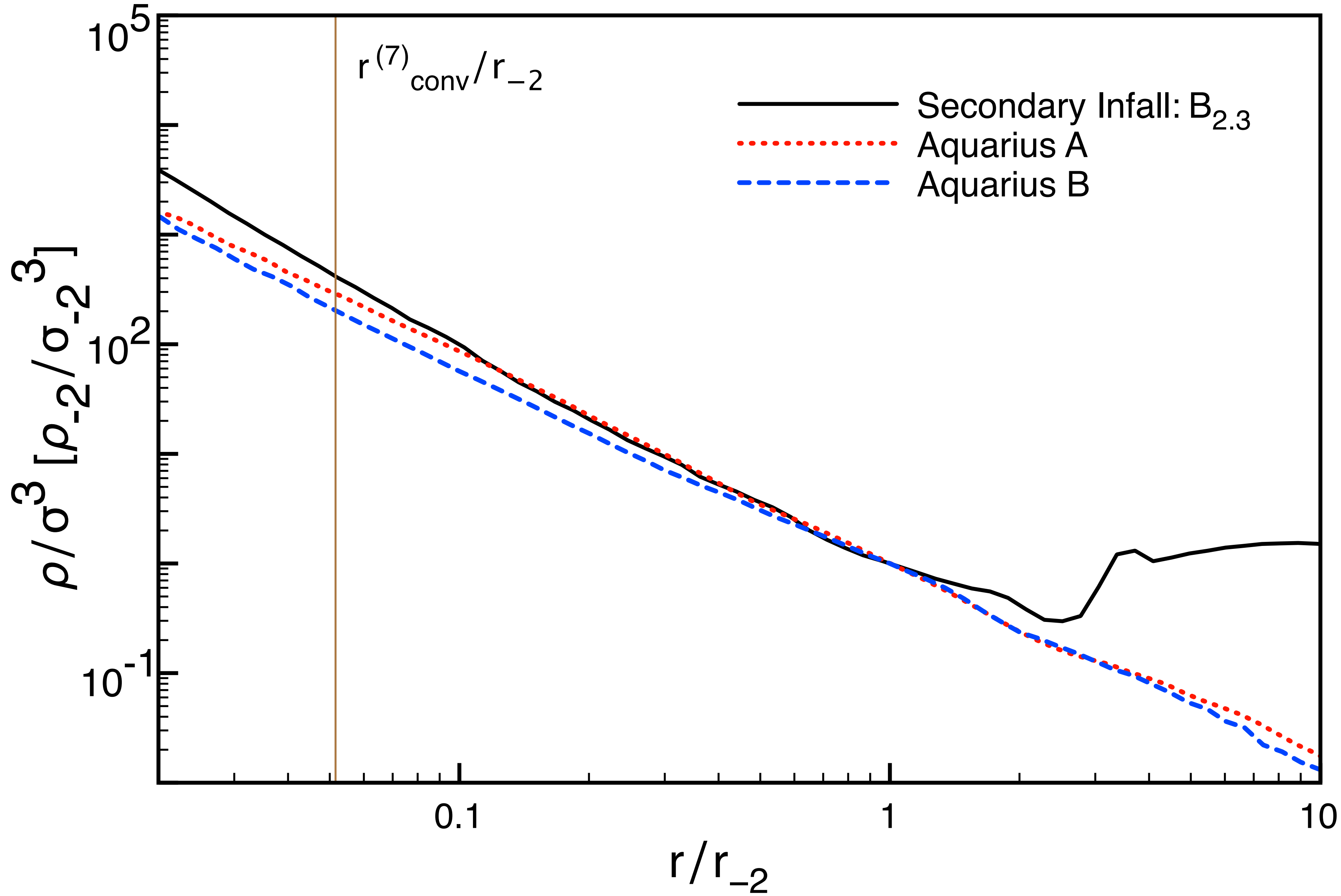
Model vs N-body: Velocity Anisotropy



Model vs N-body



Model vs N-body: Pseudo-Phase-Space Density

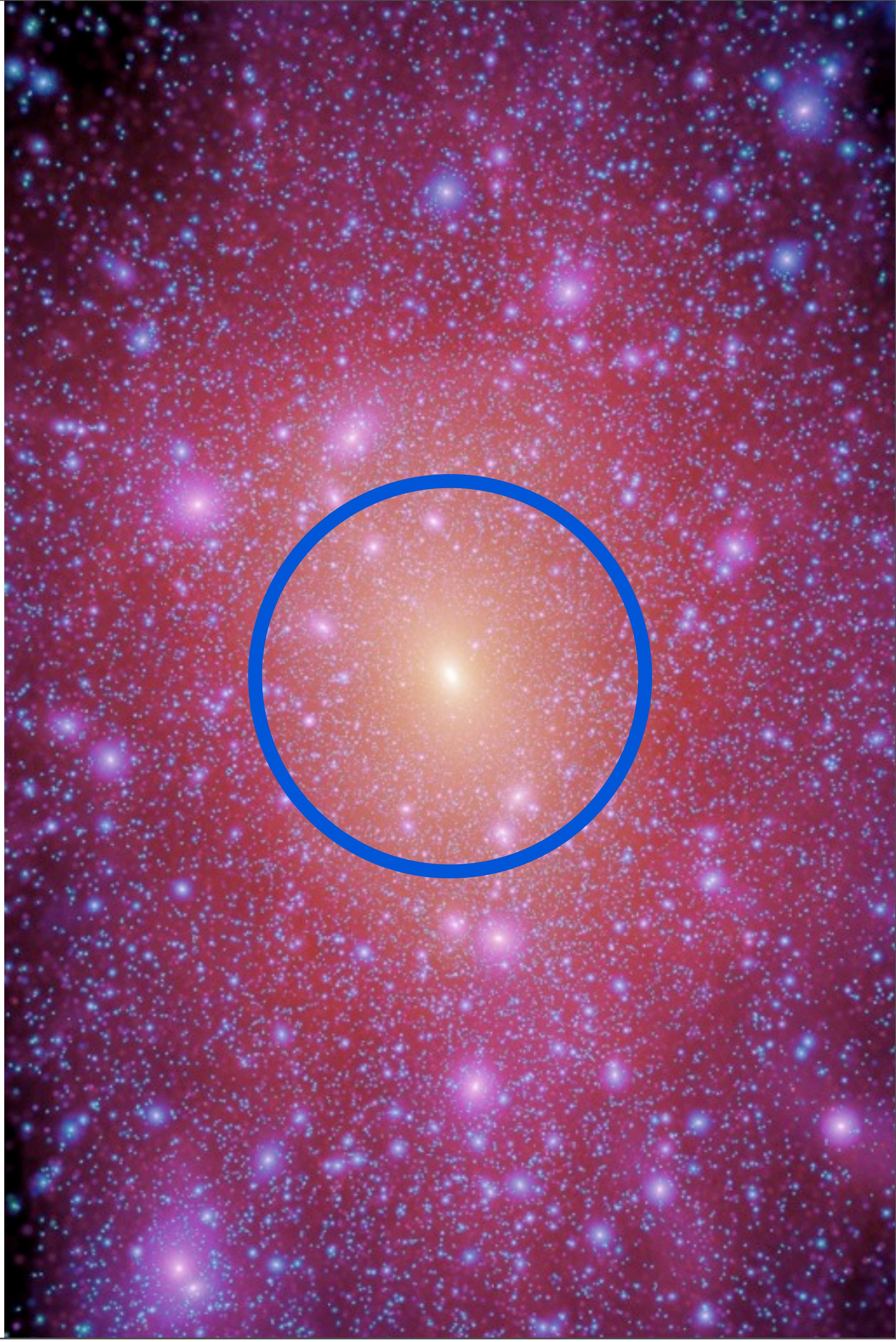


Summary

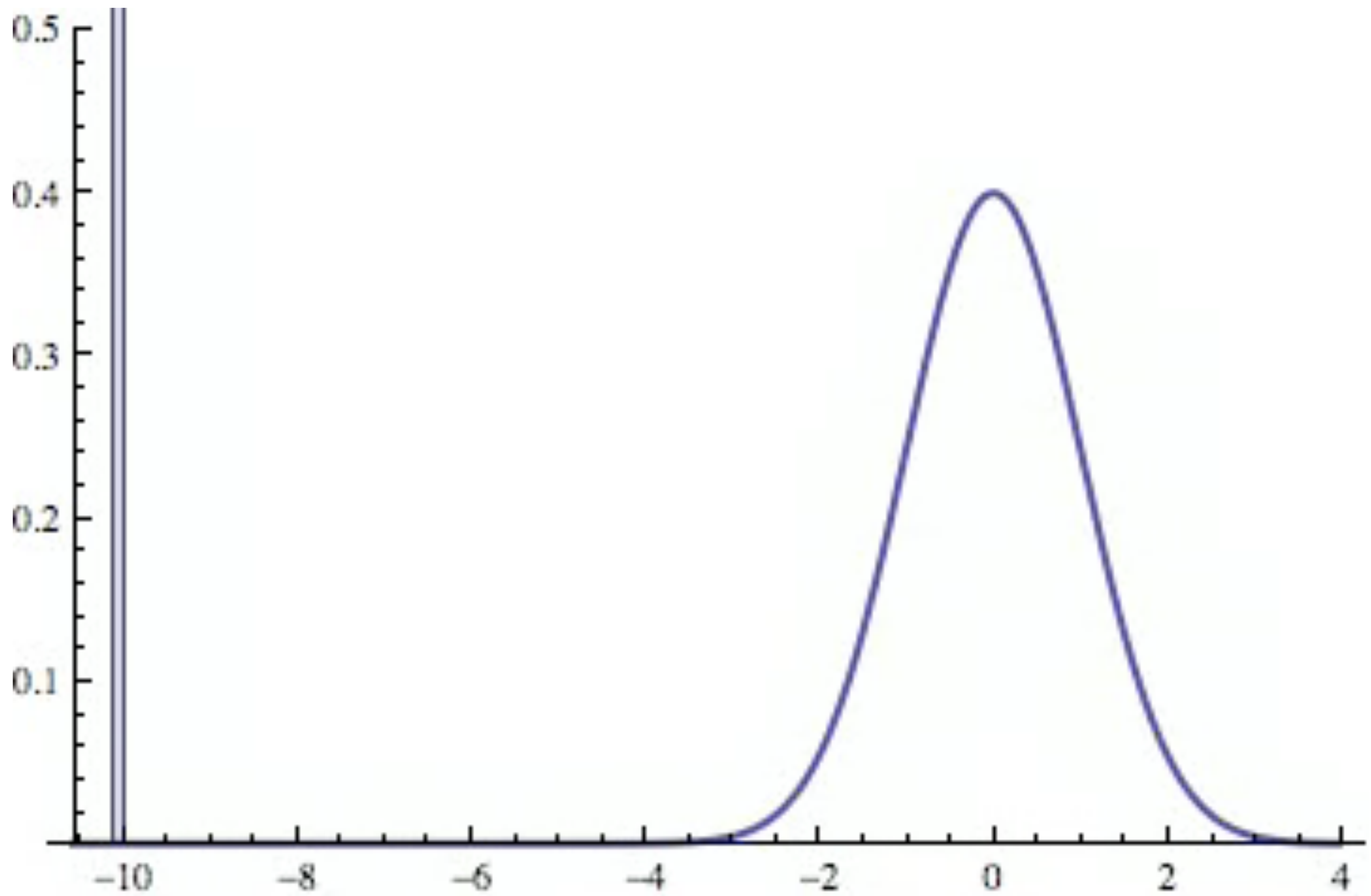
- Inner logarithmic slope of density and velocity profiles dependent on mass (n) and angular momentum evolution after turnaround (ϖ).
- Model predicts that higher resolution simulations should see deviations from universal pseudo-phase-space density relationship.
- Model is too simplistic.

Constraining ϖ

- Analyze evolution of angular momentum distribution in simulations.
- Depend on evolution of substructure? Baryons?
- Calculate for different physical processes?



Understanding Phase Space Evolution: Brownian Motion Example



What would I like to know?

- Is there an equivalent (analytic) description for Dark Matter Halos?
- Is there relaxation in a halo?

New Set of Simulations

- Aquarius Simulations (6 highly resolved halos)
- Via Lactea (1 highly resolved halo)
- Caterpillar (~150 highly resolved halos!)
- Collaborators (Anna Frebel, Lars Hernquist, Mark Vogelsberger)

Conclusions

- Self-Similar model works surprisingly well.
- How does angular momentum evolve in simulated halos (with baryons)?
- What about the phase space evolution?
- References:
    - Zukin & Bertschinger (arXiv:1008.0639, arXiv:1008.1980)
    - Navarro et. al. (arXiv:0810.1522)